US007436177B2

(12) United States Patent
Gorrell et al.

(10) **Patent No.: US 7,436,177 B2**
(45) **Date of Patent: Oct. 14, 2008**

(54) **SEM TEST APPARATUS**

(75) Inventors: **Jonathan Gorrell**, Gainesville, FL (US); **Mark Davidson**, Florahome, FL (US); **Jean Tokarz**, Hawthorne, FL (US)

(73) Assignee: **Virgin Islands Microsystems, Inc.**, Saint Thomas, VI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 334 days.

(21) Appl. No.: **11/418,081**

(22) Filed: **May 5, 2006**

(65) **Prior Publication Data**

US 2007/0256472 A1 Nov. 8, 2007

(51) **Int. Cl.**
H01J 25/50 (2006.01)

(52) **U.S. Cl.** **324/317**; 324/309; 315/39.51; 315/39.77

(58) **Field of Classification Search** 324/317, 324/309; 315/39.51, 39.77
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,948,384 A	2/1934	Lawrence	
2,307,086 A	1/1943	Varian et al.	
2,431,396 A	11/1947	Hansell	
2,473,477 A	6/1949	Smith	
2,634,372 A	4/1953	Salisbury	
2,932,798 A	4/1960	Kerst et al.	
3,571,642 A	3/1971	Westcott	
3,761,828 A	9/1973	Pollard et al.	
3,923,568 A	12/1975	Bersin	
3,989,347 A	11/1976	Eschler	
4,282,436 A	8/1981	Kapetanakos	
4,482,779 A	11/1984	Anderson	
4,727,550 A *	2/1988	Chang et al.	372/2
4,740,973 A	4/1988	Madey	
4,746,201 A	5/1988	Gould	
4,829,527 A	5/1989	Wortman et al.	
4,838,021 A	6/1989	Beattie	
5,023,563 A	6/1991	Harvey et al.	
5,157,000 A	10/1992	Elkind et al.	
5,163,118 A	11/1992	Lorenzo et al.	
5,185,073 A	2/1993	Bindra	
5,199,918 A	4/1993	Kumar	
5,262,656 A	11/1993	Blondeau et al.	
5,263,043 A	11/1993	Walsh	
5,268,693 A	12/1993	Walsh	
5,268,788 A	12/1993	Fox et al.	

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0237559 B1 12/1991

(Continued)

OTHER PUBLICATIONS

J. C. Palais, "Fiber optic communications," Prentice Hall, New Jersey, 1998, pp. 156-158.

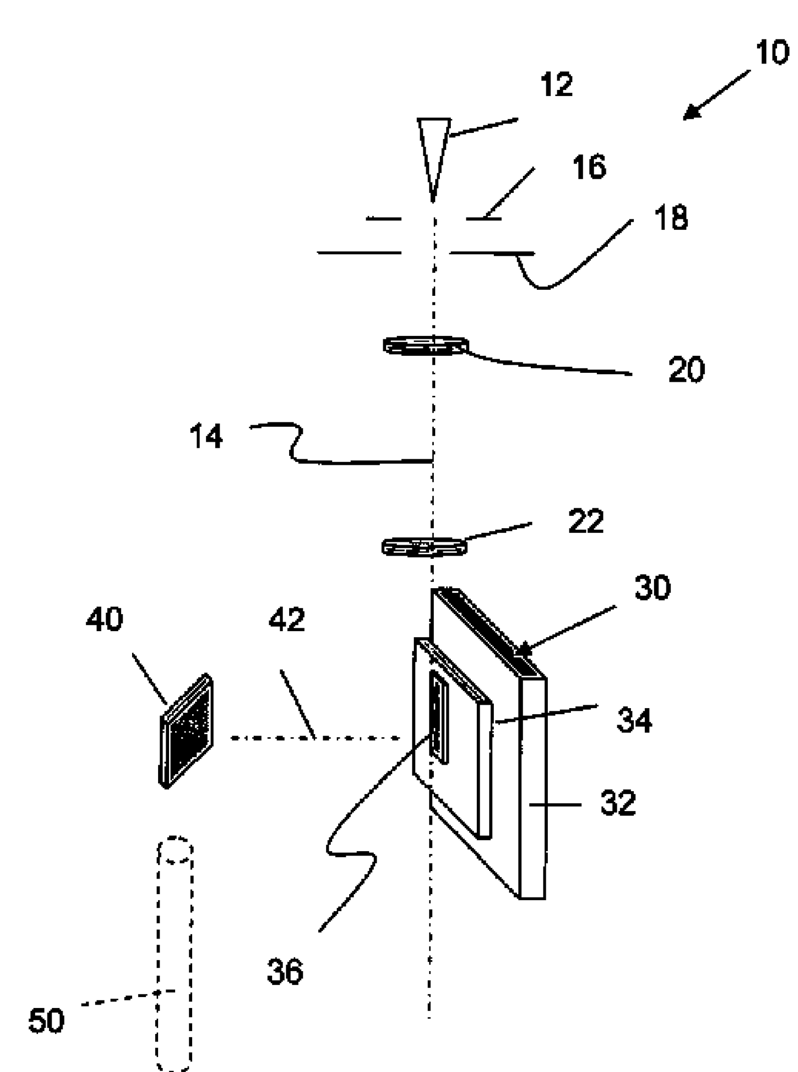
(Continued)

Primary Examiner—Kiet T Nguyen
(74) *Attorney, Agent, or Firm*—Davidson Berquist Jackson & Gowdey LLP

(57) **ABSTRACT**

Test apparatus for examining the operation and functioning of ultra-small resonant structures, and specifically using an SEM as the testing device and its electron beam as an exciting source of charged particles to cause the ultra-small resonant structures to resonate and produce EMR.

12 Claims, 3 Drawing Sheets



U.S. PATENT DOCUMENTS

5,302,240	A	4/1994	Hori et al.
5,354,709	A	10/1994	Lorenzo et al.
5,446,814	A	8/1995	Kuo et al.
5,608,263	A	3/1997	Drayton et al.
5,668,368	A	9/1997	Sakai et al.
5,705,443	A	1/1998	Stauf et al.
5,737,458	A	4/1998	Wojnarowski et al.
5,744,919	A	4/1998	Mishin et al.
5,757,009	A	5/1998	Walstrom
5,767,013	A	6/1998	Park
5,790,585	A *	8/1998	Walsh 372/102
5,811,943	A	9/1998	Mishin et al.
5,821,836	A	10/1998	Katehi et al.
5,821,902	A	10/1998	Keen
5,831,270	A	11/1998	Nakasuji
5,847,745	A	12/1998	Shimizu et al.
5,889,449	A	3/1999	Fiedziuszko
5,902,489	A	5/1999	Yasuda et al.
6,008,496	A	12/1999	Winefordner et al.
6,040,625	A	3/2000	Ip
6,060,833	A	5/2000	Velazco
6,080,529	A	6/2000	Ye et al.
6,195,199	B1	2/2001	Yamada
6,222,866	B1	4/2001	Seko
6,281,769	B1	8/2001	Fiedziuszko
6,297,511	B1	10/2001	Syllaios et al.
6,338,968	B1	1/2002	Hefti
6,370,306	B1	4/2002	Sato et al.
6,373,194	B1	4/2002	Small
6,376,258	B2	4/2002	Hefti
6,407,516	B1	6/2002	Victor
6,441,298	B1	8/2002	Thio
6,504,303	B2	1/2003	Small
6,545,425	B2	4/2003	Victor
6,577,040	B2	6/2003	Nguyen
6,603,915	B2	8/2003	Glebov et al.
6,624,916	B1	9/2003	Green et al.
6,636,653	B2	10/2003	Miracky et al.
6,642,907	B2	11/2003	Hamada et al.
6,738,176	B2	5/2004	Rabinowitz et al.
6,741,781	B2	5/2004	Furuyama
6,782,205	B2	8/2004	Trisnadi et al.
6,791,438	B2	9/2004	Takahashi et al.
6,829,286	B1	12/2004	Guilfoyle et al.
6,834,152	B2	12/2004	Gunn et al.
6,870,438	B1	3/2005	Shino et al.
6,885,262	B2	4/2005	Nishimura et al.
6,909,092	B2	6/2005	Nagahama
6,909,104	B1	6/2005	Koops
6,944,369	B2	9/2005	Deliwala
6,953,291	B2	10/2005	Liu
6,965,625	B2	11/2005	Mross et al.
6,995,406	B2	2/2006	Tojo et al.
7,010,183	B2	3/2006	Estes et al.
7,092,588	B2	8/2006	Kondo
7,092,603	B2	8/2006	Glebov et al.
7,122,978	B2	10/2006	Nakanishi et al.
7,177,515	B2	2/2007	Estes et al.
7,267,459	B2	9/2007	Matheson
7,267,461	B2	9/2007	Kan et al.
2001/0025925	A1	10/2001	Abe et al.
2002/0009723	A1	1/2002	Hefti
2002/0027481	A1	3/2002	Fiedziuszko
2002/0036264	A1	3/2002	Nakasuji et al.
2002/0053638	A1	5/2002	Winkler et al.
2002/0135665	A1	9/2002	Gardner
2003/0012925	A1	1/2003	Gorrell
2003/0016412	A1	1/2003	Small
2003/0016421	A1	1/2003	Small
2003/0034535	A1	2/2003	Barenburu et al.
2003/0155521	A1	8/2003	Feuerbaum
2003/0164947	A1	9/2003	Vaupel
2003/0179974	A1	9/2003	Estes et al.
2003/0206708	A1	11/2003	Estes et al.
2003/0214695	A1	11/2003	Abramson et al.
2004/0061053	A1	4/2004	Taniguchi et al.
2004/0108473	A1	6/2004	Melnychuk et al.
2004/0136715	A1	7/2004	Kondo
2004/0150991	A1	8/2004	Ouderkirk et al.
2004/0171272	A1	9/2004	Jin et al.
2004/0180244	A1	9/2004	Tour et al.
2004/0213375	A1	10/2004	Bjorkholm et al.
2004/0217297	A1	11/2004	Moses et al.
2004/0231996	A1	11/2004	Webb
2004/0240035	A1	12/2004	Zhilkov
2004/0264867	A1	12/2004	Kondo
2005/0023145	A1	2/2005	Cohen et al.
2005/0045821	A1	3/2005	Noji et al.
2005/0054151	A1	3/2005	Lowther et al.
2005/0067286	A1	3/2005	Ahn et al.
2005/0082469	A1	4/2005	Carlo
2005/0092929	A1	5/2005	Schneiker
2005/0105690	A1	5/2005	Pau et al.
2005/0145882	A1	7/2005	Taylor et al.
2005/0162104	A1	7/2005	Victor et al.
2005/0190637	A1	9/2005	Ichimura et al.
2005/0194258	A1	9/2005	Cohen et al.
2005/0201707	A1	9/2005	Glebov et al.
2005/0201717	A1	9/2005	Matsumura et al.
2005/0212503	A1	9/2005	Deibele
2005/0249451	A1	11/2005	Baehr-Jones et al.
2006/0007730	A1	1/2006	Nakamura et al.
2006/0018619	A1	1/2006	Helffrich et al.
2006/0035173	A1	2/2006	Davidson et al.
2006/0045418	A1	3/2006	Cho et al.
2006/0060782	A1	3/2006	Khursheed
2006/0062258	A1	3/2006	Brau et al.
2006/0159131	A1	7/2006	Liu et al.
2006/0164496	A1	7/2006	Tokutake et al.
2006/0208667	A1	9/2006	Lys et al.
2006/0216940	A1	9/2006	Gorrell et al.
2006/0243925	A1 *	11/2006	Barker et al. .... 250/504 R
2006/0274922	A1	12/2006	Ragsdale
2007/0003781	A1	1/2007	de Rochemont
2007/0013765	A1	1/2007	Hudson et al.
2007/0075264	A1 *	4/2007	Gorrell et al. 250/400
2007/0086915	A1	4/2007	LeBoeuf et al.
2007/0116420	A1	5/2007	Estes et al.

FOREIGN PATENT DOCUMENTS

JP	2004-32323	A	1/2004
WO	WO 87/01873		3/1987
WO	WO 93/21663	A1	10/1993
WO	WO 00/72413		11/2000
WO	WO 02/25785		3/2002
WO	WO 02/077607		10/2002
WO	WO 2004/086560		10/2004
WO	WO 2005/015143	A2	2/2005
WO	WO 2006/042239	A2	4/2006
WO	WO 2007/081389		7/2007
WO	WO 2007/081390		7/2007
WO	WO 2007/081391		7/2007

OTHER PUBLICATIONS

Search Report and Written Opinion mailed Dec. 20, 2007 in PCT Appln. No. PCT/US2006/022771.

Search Report and Written Opinion mailed Jan. 31, 2008 in PCT Appln. No. PCT/US2006/027427.

Search Report and Written Opinion mailed Jan. 8, 2008 in PCT Appln. No. PCT/US2006/028741.

Search Report and Written Opinion mailed Mar. 11, 2008 in PCT Appln. No. PCT/US2006/022679.

U.S. Appl. No. 11/418,082, filed May 5, 2006, Gorrell et al.

Lee Kwang-Cheol et al., "Deep X-Ray Mask with Integrated Actuator for 3D Microfabrication", Conference: Pacific Rim Workshop on Transducers and Micro/Nano Technologies, (Xiamen CHN), Jul. 22, 2002.
Markoff, John, "A Chip That Can Transfer Data Using Laser Light," The New York Times, Sep. 18, 2006.
S.M. Sze, "Semiconductor Devices Physics and Technology", 2nd Edition, Chapters 9 and 12, Copyright 1985, 2002.
Search Report and Written Opinion mailed Feb. 12, 2007 in PCT Appln. No. PCT/US2006/022682.
Search Report and Written Opinion mailed Feb. 20, 2007 in PCT Appln. No. PCT/US2006/022676.
Search Report and Written Opinion mailed Feb. 20, 2007 in PCT Appln. No. PCT/US2006/022772.
Search Report and Written Opinion mailed Feb. 20, 2007 in PCT Appln. No. PCT/US2006/022780.
Search Report and Written Opinion mailed Feb. 21, 2007 in PCT Appln. No. PCT/US2006/022684.
Search Report and Written Opinion mailed Jan. 17, 2007 in PCT Appln. No. PCT/US2006/022777.
Search Report and Written Opinion mailed Jan. 23, 2007 in PCT Appln. No. PCT/US2006/022781.
Search Report and Written Opinion mailed Mar. 7, 2007 in PCT Appln. No. PCT/US2006/022775.
Speller et al., "A Low-Noise MEMS Accelerometer for Unattended Ground Sensor Applications", Applied MEMS Inc., 12200 Parc Crest, Stafford, TX, USA 77477.
Thurn-Albrecht et al., "Ultrahigh-Density Nanowire Arrays Grown in Self-Assembled Diblock Copolymer Templates", Science 290. 5499, Dec. 15, 2000, pp. 2126-2129.
"Array of Nanoklystrons for Frequency Agility or Redundancy," NASA's Jet Propulsion Laboratory, NASA Tech Briefs, NPO-21033. 2001.
"Hardware Development Programs," Calabazas Creek Research, Inc. found at http://calcreek.com/hardware.html.
"Antenna Arrays." May 18, 2002. www.tpub.com/content/neets/14183/ccs/14183_159.htm.
"Diffraction Grating," hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html.
Alford, T.L. et al., "Advanced silver-based metallization patterning for ULSI applications," Microelectronic Engineering 55, 2001, pp. 383-388, Elsevier Science B.V.
Amato, Ivan, "An Everyman's Free-Election Laser?" Science, New Series, Oct. 16, 1992, p. 401, vol. 258 No. 5081, American Association for the Advancement of Science.
Andrews, H.L. et al., "Dispersion and Attenuation in a Smith-Purcell Free Electron Laser," The American Physical Society, Physical Review Special Topics—Accelerators and Beams 8 (2005), pp. 050703-1-050703-9.
Backe, H. et al. "Investigation of Far-Infrared Smith-Purcell Radiation at the 3.41 MeV Electron Injector Linac of the Mainz Microtron MAMI," Institut fur Kernphysik, Universitat Mainz, D-55099, Mainz Germany.
Bakhtyari, A. et al., "Horn Resonator Boosts Miniature Free-Electron Laser Power," Applied Physics Letters, May 12, 2003, pp. 3150-3152, vol. 82, No. 19, American Institute of Physics.
Bakhtyari, Dr. Arash, "Gain Mechanism in a Smith-Purcell MicroFEL," Abstract, Department of Physics and Astronomy, Dartmouth College.
Bhattacharjee, Sudeep et al., "Folded Waveguide Traveling-Wave Tube Sources for Terahertz Radiation." IEEE Transactions on Plasma Science, vol. 32. No. 3, Jun. 2004, pp. 1002-1014.
Booske, J.H. et al., "Microfabricated TWTs as High Power, Wideband Sources of THz Radiation".
Brau, C.A. et al., "Gain and Coherent Radiation from a Smith-Purcell Free Electron Laser," Proceedings of the 2004 FEL Conference, pp. 278-281.
Brownell, J.H. et al., "Improved μFEL Performance with Novel Resonator," Jan. 7, 2005, from website: www.frascati.enea.it/thz-bridge/workshop/presentations/Wednesday/We-07-Brownell.ppt.
Brownell, J.H. et al., "The Angular Distribution of the Power Produced by Smith-Purcell Radiation," J. Phys. D: Appl. Phys. 1997, pp. 2478-2481, vol. 30, IOP Publishing Ltd., United Kingdom.
Chuang, S.L. et al., "Enhancement of Smith-Purcell Radiation from a Grating with Surface-Plasmon Excitation," Journal of the Optical Society of America, Jun. 1984, pp. 672-676, vol. 1 No. 6, Optical Society of America.
Chuang, S.L. et al., "Smith-Purcell Radiation from a Charge Moving Above a Penetrable Grating," IEEE MTT-S Digest, 1983, pp. 405-406, IEEE.
Far-IR, Sub-MM & MM Detector Technology Workshop list of manuscripts, session 6 2002.
Feltz, W.F. et al., "Near-Continuous Profiling of Temperature, Moisture, and Atmospheric Stabilty Using the Atmospheric Emitted Radiance Interferometer (AERI)," Journal of Applied Meteorology, May 2003, vol. 42 No. 5, H.W. Wilson Company, pp. 584-597.
Freund, H. P. et al., "Linearized Field Theory of a Smith-Purcell Traveling Wave Tube," IEEE Transactions on Plasma Science, Jun. 2004, pp. 1015-1027, vol. 32 No. 3, IEEE.
Gallerano, G. P. et al., "Overview of Terahertz Radiation Sources," Proceedings of the 2004 FEL Conference, pp. 216-221.
Goldstein, M. et al., "Demonstration of a Micro Far-Infrared Smith-Purcell Emitter," Applied Physics Letters, Jul. 28, 1997, pp. 452-454, vol. 71 No. 4, American Institute of Physics.
Gover, A. et al., "Angular Radiation Pattern of Smith-Purcell Radiation," Journal of the Optical Society of America, Oct. 1984, pp. 723-728, vol. 1 No. 5, Optical Society of America.
Grishin, Yu. A. et al., "Pulsed Orotron—A New Microwave Source for Submillimeter Pulse High-Field Electron Paramagnetic Resonance Spectroscopy," Review of Scientific Instruments, Sep. 2004, pp. 2926-2936, vol. 75 No. 9, American Institute of Physics.
Ishizuka, H. et al., "Smith-Purcell Experiment Utilizing a Field-Emitter Array Cathode: Measurements of Radiation," Nuclear Instruments and Methods in Physics Research, 2001, pp. 593-598, A 475, Elsevier Science B.V.
Ishizuka, H. et al., "Smith-Purcell Radiation Experiment Using a Field-Emission Array Cathode," Nuclear Instruments and Methods in Physics Research, 2000, pp. 276-280, A 445, Elsevier Science B.V.
Ives, Lawrence et al., "Development of Backward Wave Oscillators for Terahertz Applications," Terahertz for Military and Security Applications, Proceedings of SPIE vol. 5070 (2003), pp. 71-82.
Ives, R. Lawrence, "IVEC Summary, Session 2, Sources I" 2002.
Jonietz, Erika, "Nano Antenna Gold nanospheres show path to all-optical computing," Technology Review, Dec. 2005/Jan. 2006, p. 32.
Joo, Youngcheol et al., "Air Cooling of IC Chip with Novel Microchannels Monolithically Formed on Chip Front Surface," Cooling and Thermal Design of Electronic Systems (HTD-vol. 319 & EEP-vol. 15), International Mechanical Engineering Congress and Exposition, San Francisco, CA Nov 1995 pp. 117-121.
Joo, Youngcheol et al., "Fabrication of Monolithic Microchannels for IC Chip Cooling," 1995, Mechanical, Aerospace and Nuclear Engineering Department, University of California at Los Angeles.
Jung, K.B. et al., "Patterning of Cu, Co, Fe, and Ag for magnetic nanostructures," J. Vac. Sci. Technol. A 15(3), May/Jun. 1997, pp. 1780-1784.
Kapp, Oscar H. et al., "Modification of a Scanning Electron Microscope to Produce Smith-Purcell Radiation," Review of Scientific Instruments, Nov. 2004, pp. 4732-4741, vol. 75 No. 11, American Institute of Physics.
Kiener, C. et al., "Investigation of the Mean Free Path of Hot Electrons in GaAs/AlGaAs Heterostructures," Semicond. Sci. Technol., 1994, pp. 193-197, vol. 9, IOP Publishing Ltd., United Kingdom.
Kim, Shang Hoon, "Quantum Mechanical Theory of Free-Electron Two-Quantum Stark Emission Driven by Transverse Motion," Journal of the Physical Society of Japan, Aug. 1993, vol. 62 No. 8, pp. 2528-2532.
Korbly, S.E. et al., "Progress on a Smith-Purcell Radiation Bunch Length Diagnostic," Plasma Science and Fusion Center, MIT, Cambridge, MA.
Kormann, T. et al., "A Photoelectron Source for the Study of Smith-Purcell Radiation".
Kube, G. et al., "Observation of Optical Smith-Purcell Radiation at an Electron Beam Energy of 855 MeV," Physical Review E, May 8, 2002, vol. 65, The American Physical Society, pp. 056501-1-056501-15.

Liu, Chuan Sheng, et al., "Stimulated Coherent Smith-Purcell Radiation from a Metallic Grating," IEEE Journal of Quantum Electronics, Oct. 1999, pp. 1386-1389, vol. 35, No. 10, IEEE.
Manohara, Harish et al., "Field Emission Testing of Carbon Nanotubes for THz Frequency Vacuum Microtube Sources." Abstract. Dec. 2003. from SPIEWeb.
Manohara, Harish M. et al., "Design and Fabrication of a THz Nanoklystron".
Manohara, Harish M. et al., "Design and Fabrication of a THz Nanoklystron" (www.sofia.usra.edu/det_workshop/ posters/session 3/3-43 manohara_poster.pdf), PowerPoint Presentation.
McDaniel, James C. et al., "Smith-Purcell Radiation in the High Conductivity and Plasma Frequency Limits," Applied Optics, Nov. 15, 1989, pp. 4924-4929, vol. 28 No. 22, Optical Society of America.
Meyer, Stephan, "Far IR, Sub-MM &MM Detector Technology Workshop Summary," Oct. 2002. (may date the Manohara documents).
Mokhoff, Nicolas, "Optical-speed light detector promises fast space talk," EETimes Online, Mar. 20, 2006, from website: www.eetimes.com/showArticle.jhtml?articleID=183701047.
Nguyen, Phucanh et al., "Novel technique to pattern silver using CF4 and CF4/O2 glow discharges," J.Vac. Sci. Technol. B 19(1), Jan./Feb. 2001, American Vacuum Society, pp. 158-165.
Nguyen, Phucanh et al., "Reactive ion etch of patterned and blanket silver thin films in Cl2/O2 and O2 glow discharges," J. Vac. Sci, Technol. B. 17 (5), Sep./Oct. 1999, American Vacuum Society, pp. 2204-2209.
Ohtaka, Kazou, "Smith-Purcell Radiation from Metallic and Dielectric Photonic Crystals," Center for Frontier Science, pp. 272-273, Chiba University, 1-33 Yayoi, Inage-ku, Chiba-shi, Japan.
Phototonics Research, "Surface-Plasmon-Enhanced Random Laser Demonstrated," Phototonics Spectra, Feb. 2005, pp. 112-113.
Platt, C.L. et al., "A New Resonator Design for Smith-Purcell Free Electron Lasers," 6Q19, p. 296.
Potylitsin, A.P., "Resonant Diffraction Radiation and Smith-Purcell Effect," (Abstract), arXiv: physics/9803043 v2 Apr. 13, 1998.
Potylitsyn, A.P., "Resonant Diffraction Radiation and Smith-Purcell Effect," Physics Letters A, Feb. 2, 1998, pp. 112-116, A 238, Elsevier Science B.V.
S. Hoogland et al., "A solution-processed 1.53 μm quantum dot laser with temperature-invariant emission wavelength," Optics Express, vol. 14, No. 8, Apr. 17, 2006, pp. 3273-3281.
Savilov, Andrey V., "Stimulated Wave Scattering in the Smith-Purcell FEL," IEEE Transactions on Plasma Science, Oct. 2001, pp. 820-823, vol. 29 No. 5, IEEE.
Schachter, Levi et al., "Smith-Purcell Oscillator in an Exponential Gain Regime," Journal of Applied Physics, Apr. 15, 1989, pp. 3267-3269, vol. 65 No. 8, American Institute of Physics.
Schachter, Levi, "Influence of the Guiding Magnetic Field on the Performance of a Smith-Purcell Amplifier Operating in the Weak Compton Regime," Journal of the Optical Society of America, May 1990, pp. 873-876, vol. 7 No. 5, Optical Society of America.
Schachter, Levi, "The Influence of the Guided Magnetic Field on the Performance of a Smith-Purcell Amplifier Operating in the Strong Compton Regime," Journal of Applied Physics, Apr. 15, 1990, pp. 3582-3592, vol. 67 No. 8, American Institute of Physics.
Shih, I. et al., "Experimental Investigations of Smith-Purcell Radiation," Journal of the Optical Society of America, Mar. 1990, pp. 351-356, vol. 7, No. 3, Optical Society of America.
Shih, I. et al., "Measurements of Smith-Purcell Radiation," Journal of the Optical Society of America, Mar. 1990, pp. 345-350, vol. 7 No. 3, Optical Society of America.
Swartz, J.C. et al., "THz-FIR Grating Coupled Radiation Source," Plasma Science, 1998, 1D02, p. 126.
Temkin, Richard, "Scanning with Ease Through the Far Infrared," Science, New Series, May 8, 1998, p. 854, vol. 280, No. 5365, American Association for the Advancement of Science.
Walsh, J.E., et al., 1999. From website: http://www.ieee.org/organizations/pubs/newsletters/leos/feb99/hot2.htm.
Wentworth, Stuart M. et al., "Far-Infrared Composite Microbolometers," IEEE MTT-S Digest, 1990, pp. 1309-1310.
Yamamoto, N. et al., "Photon Emission From Silver Particles Induced by a High-Energy Electron Beam," Physical Review B, Nov. 6, 2001, pp. 205419-1-205419-9, vol. 64, The American Physical Society.
Yokoo, K. et al., "Smith-Purcell Radiation at Optical Wavelength Using a Field-Emitter Array," Technical Digest of IVMC, 2003, pp. 77-78.
Zeng, Yuxiao et al., "Processing and encapsulation of silver patterns by using reactive ion etch and ammonia anneal," Materials Chemistry and Physics 66, 2000, pp. 77-82.
Search Report and Written Opinion mailed Aug. 24, 2007 in PCT Appln. No. PCT/US2006/022768.
Search Report and Written Opinion mailed Aug. 31, 2007 in PCT Appln. No. PCT/US2006/022680.
Search Report and Written Opinion mailed Jul. 16, 2007 in PCT Appln. No. PCT/US2006/022774.
Search Report and Written Opinion mailed Jul. 20, 2007 in PCT Appln. No. PCT/US2006/024216.
Search Report and Written Opinion mailed Jul. 26, 2007 in PCT Appln. No. PCT/US2006/022776.
Search Report and Written Opinion mailed Jun. 20, 2007 in PCT Appln. No. PCT/US2006/022779.
Search Report and Written Opinion mailed Sep. 12, 2007 in PCT Appln. No. PCT/US2006/022767.
Search Report and Written Opinion mailed Sep. 13, 2007 in PCT Appln. No. PCT/US2006/024217.
Search Report and Written Opinion mailed Sep. 17, 2007 in PCT Appln. No. PCT/US2006/022787.
Search Report and Written Opinion mailed Sep. 5, 2007 in PCT Appln. No. PCT/US2006/027428.
Search Report and Written Opinion mailed Sep. 17, 2007 in PCT Appln. No. PCT/US2006/022689.
International Search Report and Written Opinion mailed Nov. 23, 2007 in International Application No. PCT/US2006/022786.
Search Report and Written Opinion mailed Oct. 25, 2007 in PCT Appln. No. PCT/US2006/022687.
Search Report and Written Opinion mailed Oct. 26, 2007 in PCT Appln. No. PCT/US2006/022675.
Search Report and Written Opinion mailed Sep. 21, 2007 in PCT Appln. No. PCT/US2006/022688.
Search Report and Written Opinion mailed Sep. 25, 2007 in PCT appln. No. PCT/US2006/022681.
Search Report and Written Opinion mailed Sep. 26, 2007 in PCT Appln. No. PCT/US2006/024218.

* cited by examiner

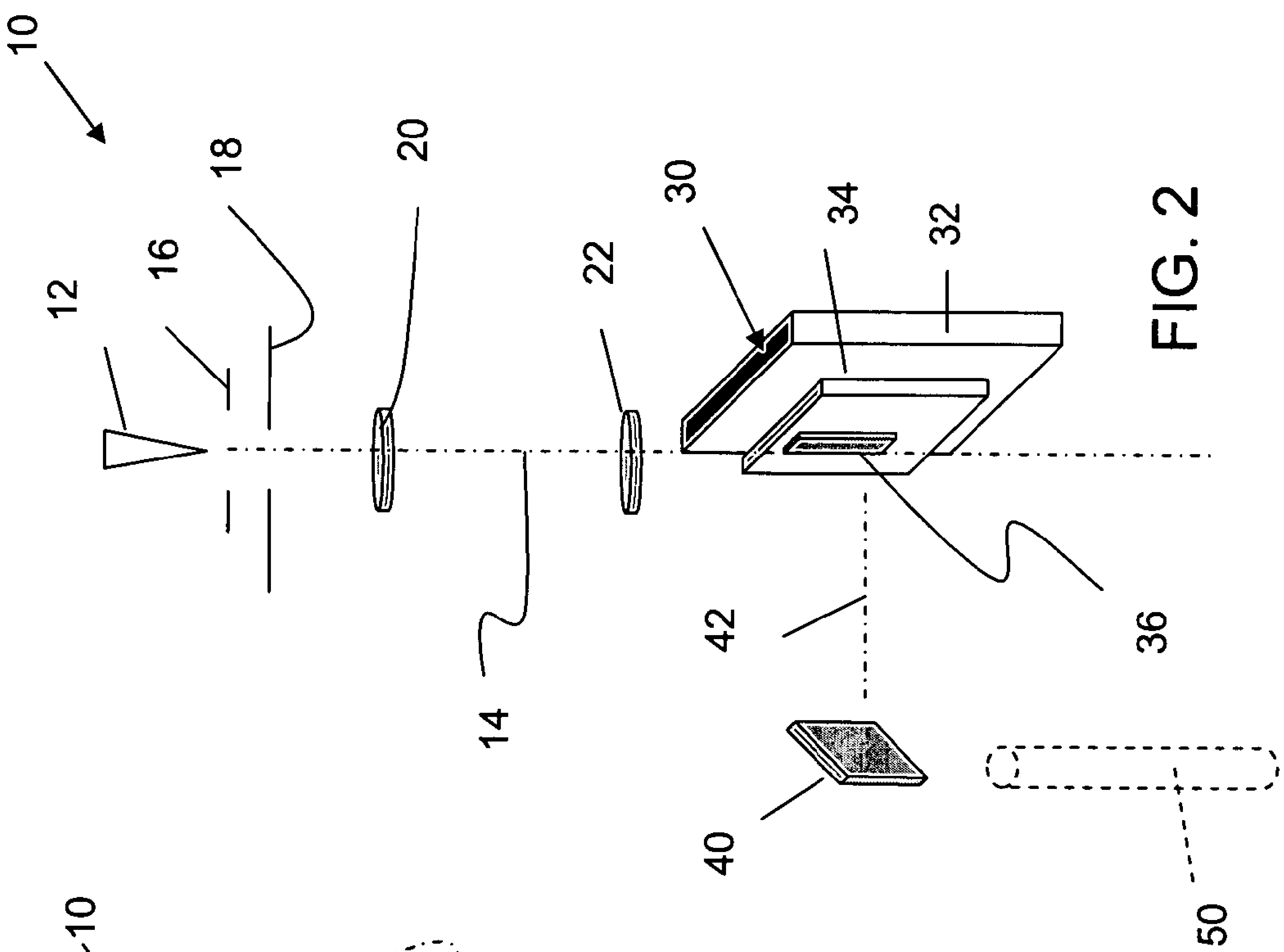

10
12
16
18
20
22
30
34
32
14
42
36
40
50

FIG. 2

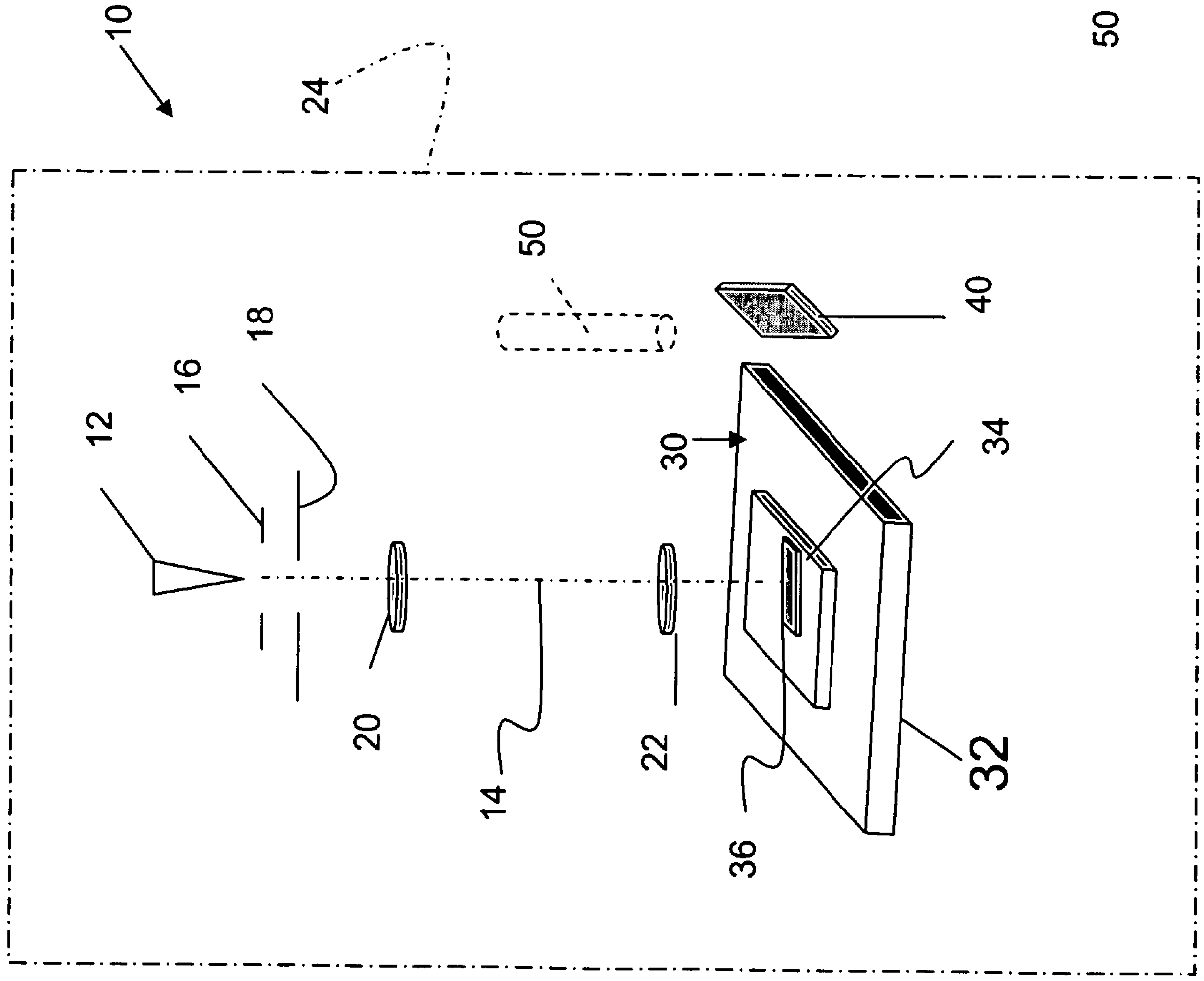

10
24
12
16
18
50
40
30
34
20
14
22
32
36

FIG. 1

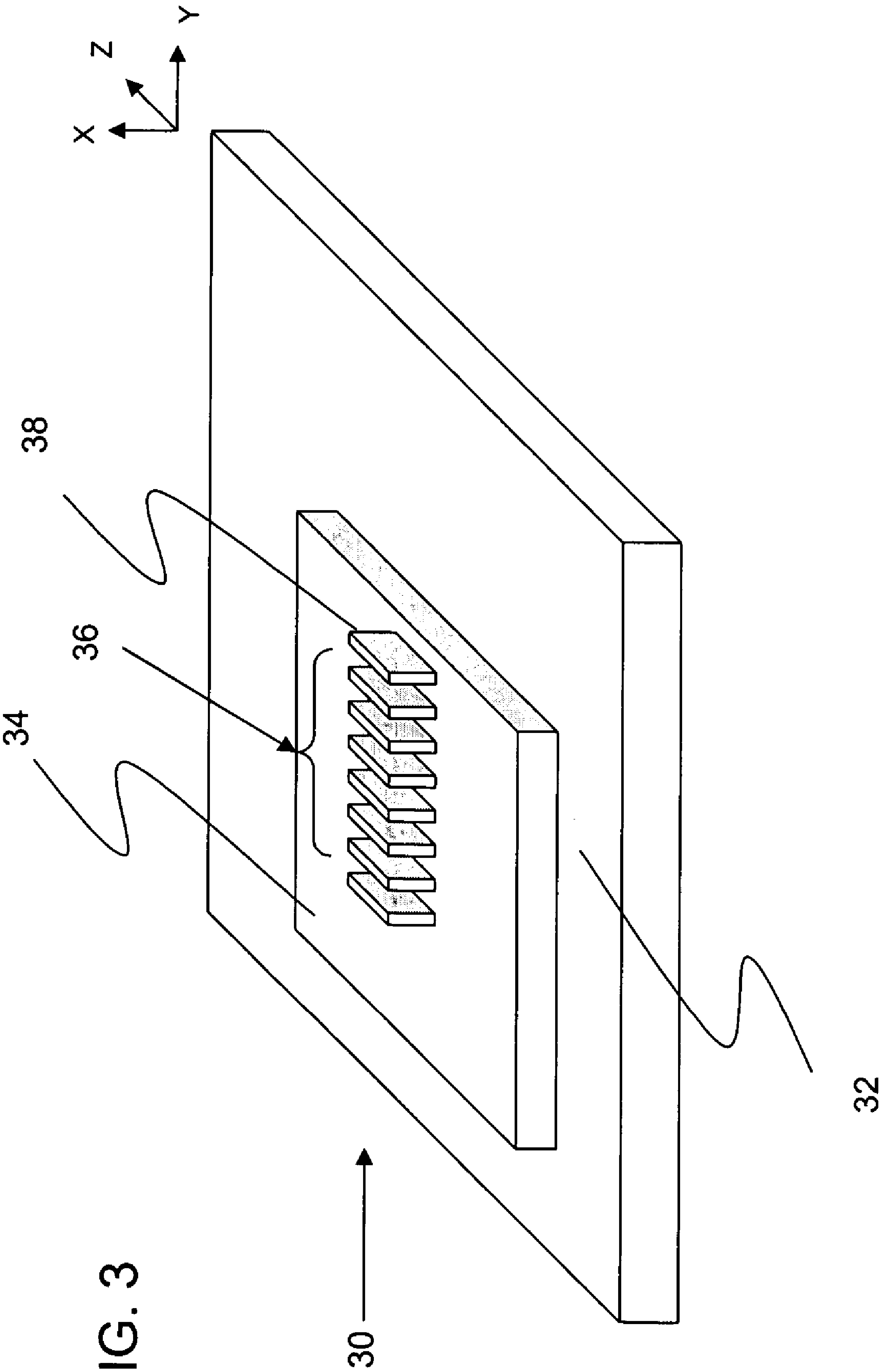


FIG. 3

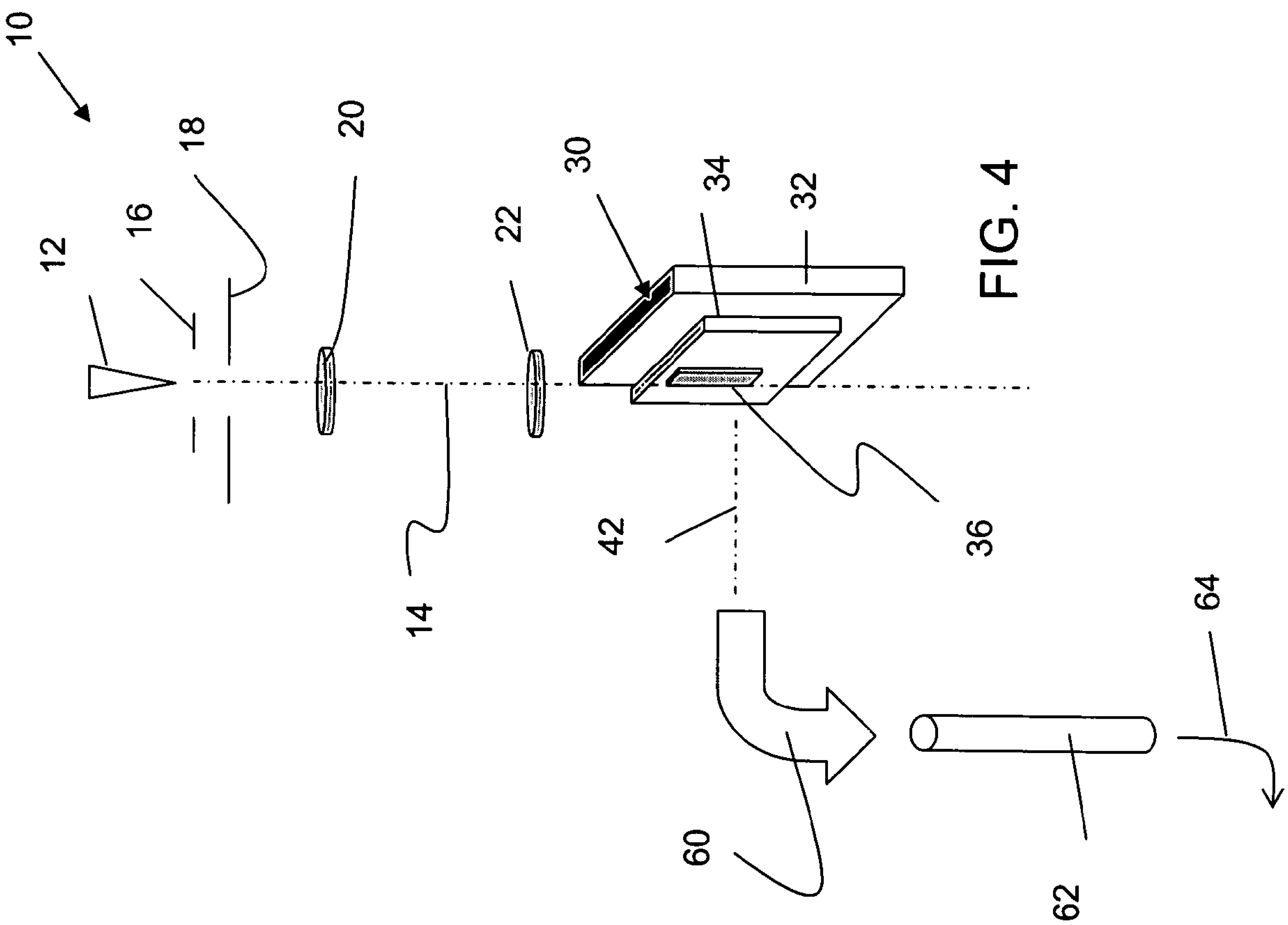


FIG. 4

SEM TEST APPARATUS

COPYRIGHT NOTICE

CROSS-REFERENCE TO CO-PENDING APPLICATIONS

The present invention is related to the following co-pending U.S. patent applications: (1) U.S. patent application Ser. No. 11/238,991, filed Sep. 30, 2005, entitled "Ultra-Small Resonating Charged Particle Beam Modulator"; (2) U.S. patent application Ser. No. 10/917,511, filed on Aug. 13, 2004, entitled "Patterning Thin Metal Film by Dry Reactive Ion Etching"; (3) U.S. application Ser. No. 11/203,407, filed on Aug. 15, 2005, entitled "Method Of Patterning Ultra-Small Structures"; (4) U.S. application Ser. No. 11/243,476, filed on Oct. 5, 2005, entitled "Structures And Methods For Coupling Energy From An Electromagnetic Wave"; (5) U.S. application Ser. No. 11/243,477, filed on Oct. 5, 2005, entitled "Electron beam induced Resonance"; (6) U.S. application Ser. No. 11/325,432, entitled "Resonant Structure-Based Display," filed on Jan. 5, 2006; (7) U.S. application Ser. No. 11/325,571, entitled "Switching Micro-Resonant Structures By Modulating A Beam Of Charged Particles," filed on Jan. 5, 2006; (8) U.S. application Ser. No. 11/325,534, entitled "Switching Micro-Resonant Structures Using At Least One Director," filed on Jan. 5, 2006; (9) U.S. application Ser. No. 11/350,812, entitled "Conductive Polymers for the Electroplating", filed on Feb. 10, 2006; (10) U.S. application Ser. No. 11/302,471, entitled "Coupled Nano-Resonating Energy Emitting Structures," filed on Dec. 14, 2005; and (11) U.S. application Ser. No. 11/325,448, entitled "Selectable Frequency Light Emitter", filed on Jan. 5, 2006, which are all commonly owned with the present application, the entire contents of each of which are incorporated herein by reference.

FIELD OF THE DISCLOSURE

This disclosure relates to the use and testing of ultra-small resonant structures, and arrays formed there from, together with the formation of associated structures located adjacent such ultra-small resonant structures, and specifically an approach for checking the operation of ultra-small resonant structures as they are excited by beams of charged particles directed there past within, for example, a high resolution, scanning electron microscope, a high resolution, field emission scanning electron microscope (FE-SEM) or an environmental scanning electron microscope (ESEM) (collectively referred to herein as an "SEM"), and light or other electromagnetic radiation (EMR) produced by the excited ultra-small resonant structures.

INTRODUCTION

Ultra-small structures encompass a range of structure sizes sometimes described as micro- or nano-sized. Objects with dimensions measured in ones, tens or hundreds of microns are described as micro-sized. Objects with dimensions measured

in ones, tens or hundreds of nanometers or less are commonly designated nano-sized. Ultra-small hereinafter refers to structures and features ranging in size from hundreds of microns in size to ones of nanometers in size.

The devices of the present invention produce electromagnetic radiation (EMR), light or energy in a variety of spectrums by the excitation of ultra-small resonant structures. The resonant excitation in a device according to the invention is induced by electromagnetic interaction which is caused, e.g., by the passing of a charged particle beam in close proximity to the device. The charged particle beam can include ions (positive or negative), electrons, protons and the like. The beam may be produced by any source, including, e.g., without limitation an ion gun, a tungsten filament, a cathode, a planar vacuum triode, an electron-impact ionizer, a laser ionizer, a chemical ionizer, a thermal ionizer, an ion-impact ionizer. It is desirable to be able to quickly test the operation of ultra-small resonant structures formed on a substrate, to test such ultra-small resonant structures in a quick yet precise manner, and in apparatus that requires minimal set up. It is equally important that alignment of the beam of charged particles and the ultra-small resonant structures to be excited can be accomplished very precisely and under controlled and repeatable conditions.

Glossary: As used throughout this document:

The phrase "ultra-small resonant structure" shall mean any structure of any material, type or microscopic size that by its characteristics causes electrons to resonate at a frequency in excess of the microwave frequency.

The term "ultra-small" within the phrase "ultra-small resonant structure" shall mean microscopic structural dimensions and shall include so-called "micro" structures, "nano" structures, or any other very small structures that will produce resonance at frequencies in excess of microwave frequencies.

DESCRIPTION OF PRESENTLY PREFERRED EXAMPLES OF THE INVENTION

BRIEF DESCRIPTION OF FIGURES

The invention is better understood by reading the following detailed description with reference to the accompanying drawings in which:

FIG. **1** is a diagrammatic showing of a scanning electron microscope (SEM) based test apparatus;

FIG. **2** is a diagrammatic showing of an SEM where a nano-stage has been mounted and moved to orient an array of ultra-small resonant structures relative to a beam of charged particles within the SEM;

FIG. **3** shows an enlarged view of the nano-stage and its positions of movement; and

FIG. **4** shows another approach for detecting the EMR produced by the ultra-small resonant structures.

DESCRIPTION

Ultra-small resonating structures can be constructed with many types of materials. Examples of suitable fabrication materials include silver, copper, gold, and other high conductivity metals, and high temperature superconducting materials. The material may be opaque or semi-transparent. In the above-identified patent applications, ultra-small structures for producing electromagnetic radiation are disclosed, and methods of making the same. In at least one embodiment, the resonant structures of the present invention are made from at least one layer of metal (e.g., silver, gold, aluminum, platinum or copper or alloys made with such metals); however, multiple layers and non-metallic structures (e.g., carbon nanotubes and high temperature superconductors) can be utilized, as long as the structures are excited by the passage of a charged particle beam. The materials making up the resonant structures may be deposited on a substrate and then etched, electroplated, or otherwise processed to create a number of individual resonant elements. The material need not even be a contiguous layer, but can be a series of resonant elements individually present on a substrate. The materials making up the resonant elements can be produced by a variety of methods, such as by pulsed-plating, depositing or etching. Preferred methods for doing so are described in co-pending U.S. application Ser. No. 10/917,571 and Ser. No. 11/203,407, both of which were previously referenced above and incorporated herein by reference.

It is desirable to be able to have a convenient test apparatus to determine whether the ultra-small resonant structures work as expected and desired when excited by passing a beam of charged particles there past, as well as to look at and study the effects of how the out put of the ultra-small resonant structures may change as the exciting conditions change or as a result of modifications in their spacing, design, or shape, or as the type and power within the beam of charged particles is modified, as well as other aspects of the operation of such devices.

With reference to FIG. **1**, a diagrammatic representation of a scanning electron microscope (SEM) **10** is set forth and includes a source **12** of a beam **14** of charged particles. Such a beam is usually focused or controlled to confine it by a suitable beam control **16**, such as Wehnelt, or other similar beam control device that is part of the SEM, and an anode **18**. An SEM will also include one or more condenser lenses **20** and an objective lens **22** to direct the beam within the microscope. Since SEM's are well known to those skilled in the art, further details thereof are not needed nor provided herein.

FIG. **1** also shows in phantom an outer housing **24** since the testing process will, as with SEM use, take place under vacuum conditions. Here again, the housing will differ with each model, type and manufacturer of SEM equipment thus requiring the housing to be represented only. This is not to be taken as a limiting factor with the present invention.

FIG. **1** also shows a stage to hold the sample being tested, and in particular a nano-stage for holding and positioning the array of ultra-small resonant structures. The nano-stage **30** includes a main stage **32** on which the substrate **34** is mounted and on which has been formed a light emitting device array **36**. It should be understood that the light emitting device array **36** of ultra-small resonant structures should contain two or more ultra-small resonant structures **38**, as shown in FIG. **3**, it can be formed from a plurality of ultra-small resonant structures. In addition, the light emitting device array **36** could be comprised of several arrays of ultra-small resonant structures, and the substrate **36** could be a portion of a chip, an entire chip, or a portion of a substrate being used in the formation of ultra-small resonant structures that has been cut from a larger substrate. In FIG. **1** the stage has been placed in the SEM but has not yet been oriented.

FIG. **2** shows the nano-stage **30** as having been both rotated and tilted to orient the array **36** to be aligned with and preferably parallel with the beam **14**. Nano-stage **30** has been designed to be movable in multiple directions, including at least the X, Y and Z directions, as shown by that symbol in FIG. **2**. In addition, the nano-stage **30** is also tiltable and rotatable in multiple directions and degrees. Movement in the X direction in an SEM is normally in a range of about 0 to 100 mm, but only movement in the range of 0-100 nm is required in most instances for nano-stage **30**. Movement in the Y and Z directions are usually in the range of 0-80 mm and 0-50 mm, respectively, but with the nano-stage **30**, Y and Z movement in the ranges of 0-80 nm and 0-50 nm, respectively, should be sufficient. Tilting can be in the range of about −10° and +90°. Rotation is preferably 360°. It is possible to test these devices with nano-stage control of only two translation and one rotation axis but it is preferred to have three and two, respectively. It is preferred to have control over the movement of nano-stage **30** be either manual, via a joy stick, or by having incremental movement under the control of a software or computer program that can be either pre-set or controlled by a combination of manual and/or automatic inputs. Each of these movement parameters will be visible on digital readouts or other similar displays so that it is possible to monitor and vary each parameter as an independent entity or collectively.

While it is possible to use any substrate sample with an array of ultra-small resonant structures, it is preferred that the array be formed adjacent an edge of the substrate, or that the substrate be cut so that one cut edge be directly adjacent the cut edge. This makes the orientation of the substrate and the array on the nano-stage, that is from the position shown in FIG. **1** to that shown in FIG. **2** be an easier task. Alignment of the beam **14** so that it passes across the top or side of the ultra-small resonant structures **38** can be accomplished with the array **36** located more centrally on the substrate **32**, but that alignment is made easier when the ultra-small resonant structures **38** begin close to one edge of the cut substrate **32**.

Nano-stage **30** can be driven by a variety of motorized devices, but a pico-drive motorized stage is preferred. One example is model 8081, a motorized five-axis tilt aligner, manufactured by New Focus, that can be operated and/or controlled by computerized, manual or joy-stick created signal inputs. The stage can be driven by a suitable picomotor, and the stage itself can have the following operational parameters:

Style	Five-Axis Tilt Aligner
Motorized Axes	5
Degrees of Freedom	X, Y, Z, θ_x, θ_y
Linear Travel	X, Y, Z = 3 mm
Angular Travel	θ_x, θ_y = 8°
Minimum Incremental Motion	X, Y, Z = <30 nm
Angular Resolution	θ_x, θ_y = <0.7 μrad
Maximum Load	5 lbs

Once the array **36** is aligned as desired with the beam **14**, and the ultra-small resonant structures **38** are excited, the ultra-small resonant structures will begin to resonate and produce out put energy, for example EMR or light in some spectrum. To monitor and maintain a running check on the operation of the array **36** and the individual ultra-small resonant structures **38**, one or more detectors, spectrometers, or some similar device, including a focal plane array, to receive and transmit the produced energy is needed. Such a detector **40** is shown in FIGS. **1** and **2**, and in FIG. **2** the out put energy is shown at **42**. An optical detector **50**, shown in dotted line in FIGS. **1** and **2**, can be used in place of detector **40**, or it can be used to receive the produced energy **42** and direct that to another device.

Another approach is shown in FIG. **4** where the produced energy **42** is received by an optical element **60** which can then send the received signal to a detector, such as shown at **50** in FIG. **2** that could be like one of those described above, or to another optical system **62** from which an output signal **64** is transmitted out of the microscope. With any of these detector concepts, the produced energy will ultimately be transmitted to a suitable display where the results can be seen, recorded or otherwise used and studied.

Using a SEM as a test apparatus is convenient since it has its own built in charged particle beam generator. Thus, it is only necessary to have as a sample an array of the ultra-small resonant structures on a substrate with the ability to then use the microscope's own beam to power or excite the ultra-small resonant structures. Determining the operating characteristics of any array of ultra-small resonant structures can be quickly checked, observed and modifications can be accomplished quickly and efficiently. Further, the nano-stage permits very small and precise changes in the orientation of the sample to be easily and quickly made, relative to the beam's path. This also permits multiple arrays on a sample substrate to be quickly checked by moving one and then another into alignment with the beam, or by aligning the substrate so that multiple arrays can be excited simultaneously by the beam of charged particles created within the SEM.

Devices according to the present invention are built from ultra-small resonant structures that have been formed on a suitable substrate. Thereafter, to perform testing of such devices, the substrate, or depending upon its size a portion of the substrate bearing the array to be tested can be cut out of the substrate, will be mounted on or to a stage that can be used on an electron microscope. It is preferred that the stage be movable through multiple planes and angles so that the alignment of the array within the electron microscope can be varied and changed. The stage is then placed in an electron microscope and the stage can then be positioned or oriented so that the path of the electron beam, or what ever type of beam of charged particles is being used, can be directed as desired along the array of ultra-small resonant structures. Once that stage position is established, the beam can be turned on, the array can be excited and suitable detectors, within a sight line of the energy out put from the array, such as EMR, can be received and signals generated corresponding to that out put EMR. Where movement of the beam is accomplished relative to the array during testing, for example by being deflected, where the stage itself is moved during testing, or where both the beam is deflected and the stage is moved, the detectors will receive the varying EMR being emitted in accordance with the relative movement between the array and the beam. This permits beam movement to be viewed, studied and experimented with and the results observed.

In addition, the operation of the ultra-small resonant structures frequently involves the movement or deflection of the beam of charged particles. Consequently, it is also desirable to be able to deflect the beam of charged particles coming from the source thereof with the SEM, to move or reposition the array on the stage during or as a part of the testing and exciting process, or both.

While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims.

We claim:

1. A test apparatus for examining the operation of ultra-small resonant structures comprising:

an array of ultra-small resonant structures formed on a substrate;

a SEM including a source of a beam of charged particles;

a multi-positional stage mountable within the SEM and on which the array is mounted, the stage being movable in multiple directions relative to a path of a beam of charged particles produced by the source so that the array can be oriented relative to the beam and be excited thereby.

2. The test apparatus as in claim **1** wherein the positioning of the stage is controlled to position the array relative to the beam further comprises a source of control inputs.

3. The test apparatus as in claim **1** further including at least one detector for receiving energy produced by the array when excited by the beam and at least one display operatively connected to the detector for displaying the energy produced by the array.

4. The test apparatus as in claim **3** wherein the detector includes an optical pick-up assembly.

5. The test apparatus as in claim **3** wherein the detector comprises a focal plane array.

6. The test apparatus as in claim **1** further including a beam deflector to move the beam relative to the array.

7. The test apparatus as in claim **1** wherein the stage is movable prior to and during the generation of the beam.

8. The test apparatus as in claim **1** wherein the beam is movable relative to the array.

9. The test apparatus as in claim **1** wherein multiple arrays are provided on the substrate and the beam is oriented to excite the multiple arrays.

10. The test apparatus as in claim **1** wherein the substrate comprises a chip.

11. The test apparatus as in claim **1** wherein the SEM comprises a scanning electron microscope.

12. The test apparatus as in claim **1** wherein the SEM comprises a field emission scanning electron microscope.

* * * * *